Quantification of the Interacting Physical, Biological, Optical and Chemical Properties of Thin Layers in the Sea

Dr. Margaret Anne McManus
Associate Professor of Oceanography
University of Hawaii at Manoa
Honolulu, Hawaii 96822
phone: (808) 956-8623 fax: (808) 956-9225 email: mamc@hawaii.edu

Dr. Mark T. Stacey
Professor of Civil & Environmental Engineering
University of California Berkeley
Berkeley, California 94720
phone: (510) 642-6776 fax: (510) 642-7483 email: mstacey@berkeley.edu

Dr. John P. Ryan
Research Scientist
Monterey Bay Aquarium Research Institute
Moss Landing, California 95039
phone: (831) 775-1700 fax: (831) 775-1652 email: ryjo@mbari.org

Grant Number: N00014-04-1-0311

LONG-TERM GOAL

Our long-term goal is to develop the capability to predict thin layer formation and presence in the coastal ocean.

OBJECTIVES

The central focus of our research is to investigate: The spatial and temporal scales of thin layers, the relationship between physical processes (from the microscale to the mesoscale) and thin layers, as well as the difference between layered structures in the nearshore and offshore environments. The overarching goal of our research is to ultimately determine how many physical variables are required to predict the occurrence of thin layers in the sea. Members of this research provided logistical support to all PIs in the Layered Organization in the Coastal Ocean (LOCO) Program, a Departmental Research Initiative (DRI) supported by ONR (see RELATED PROJECTS). In addition, Dr. McManus is serving as a Guest Editor for a special issue of Continental Shelf Research, featuring results from the LOCO Program.

APPROACH

We undertook two field experiments in Monterey Bay, the first in the summer of 2005, and the second in the summer of 2006. There were 4 major components to this work: (1) Deployment of moored

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**

4. TITLE AND SUBTITLE **Quantification Of The Interacting Physical, Biological, Optical And Chemical Properties Of Thin Layers In The Sea**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Hawaii at Manoa,Honolulu,HI,96822**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The central focus of our research is to investigate: The spatial and temporal scales of thin layers, the relationship between physical processes (from the microscale to the mesoscale) and thin layers, as well as the difference between layered structures in the nearshore and offshore environments. The overarching goal of our research is to ultimately determine how many physical variables are required to predict the occurrence of thin layers in the sea. Members of this research provided logistical support to all PIs in the Layered Organization in the Coastal Ocean (LOCO) Program, a Departmental Research Initiative (DRI) supported by ONR (see RELATED PROJECTS). In addition, Dr. McManus is serving as a Guest Editor for a special issue of Continental Shelf Research, featuring results from the

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

instruments used to measure physical processes, (2) shipboard surveys using a small vessel (33 ft) to quantify the relationship between finescale and microscale physical processes and thin layers, and to assess how local patterns of current velocity relate to thin layers, (3) Acrobat tow body surveys to quantify the relationship between mesoscale physical processes, thin layers and optical properties, and (4) AUV surveys to quantify the relationship between mesoscale physical processes, thin layers, optical properties and nutrients. Key individuals participating in this work are Dr. Margaret McManus (PI), Dr. Mark Stacey (PI), Dr. John Ryan (PI), Dr. Olivia Cheriton (Graduate student, PhD 2008) and Dr. Jonah Steinbuck (Graduate student, PhD 2009). Dr. McManus is recognized for her work assessing the interactions of biological and physical processes in the coastal ocean. Dr. Stacey is recognized for his work on transport and mixing in stratified flows in the coastal environment. Dr. Ryan is well known for his work on harmful algal blooms in the ocean. Dr. Cheriton was a graduate student in the McManus Laboratory at the University of California Santa Cruz. Dr. Steinbuck was a graduate student at Stanford University.

WORK COMPLETED

Instrument Deployment in the Array Site: Instruments to measure physical processes were deployed at the array sites in 2005 and 2006. In both years, the arrays were located in the northeastern corner of Monterey Bay in the vicinity of 36°56.2′N, 121° 55.8′W in water depths ranging from 18-30 m. In 2006, one bottom mounted 1200 kHz ADCP was deployed at site K1. One bottom mounted 600 kHz ADCP, and one thermistor chain were deployed at site K2. One bottom mounted 600 kHz ADCP and one thermistor chain were deployed at site NW. Finally, one bottom mounted 300 kHz ADCP and one thermistor chain were deployed at K4.

Small Vessel Surveys: Routine surveys were made in the array using a 33 ft vessel. Instrumentation on the small vessel included a slow-drop profiler (descent rate < 10 cm /s) equipped with a SeaBird SBE-25 CTD (T, S, σ_t, P), an SBE-43 (O_2), a WET Labs WetStar fluorometer (Chlorophyll a), and a WET Labs ac-9 (absorption and attenuation at nine wavelengths). Also on the profiler was a Biospherical sensor (PAR), a Nortek ADV (finescale velocity), and a SCAMP (microstructure). In addition, a downward-looking 600 kHz ADCP (current magnitude and direction) was installed on the side of the vessel. In 2006, three vessel surveys were undertaken; each encompassed a full 24-hour cycle. The 24-hr surveys were designed to span the spring-neap tidal cycle and all phases of the diurnal tidal cycle. Once on station, we profiled continuously with the high-resolution profiler every 3.5 minutes for 24 hours. There were brief breaks in our profiling cycle for downloading data from the SCAMP. The vessel mounted ADCP ran continuously during these 24-hour surveys.

Acrobat Surveys: In 2006, a SeaSciences Acrobat tow body was equipped with a SeaBird SBE-49 FastCAT CTD (T, S, σ_t, P) and a WET Labs Inc. ECO-triplet sensor (chlorophyll-a, CDOM, and backscatter at 660nm). Three surveys were performed along transects southeast of the LOCO array. The first two surveys, on July 25 and 26, took place during daytime hours and were performed using the MBARI Zephyr research vessel. The third survey, on 27-28 July 2006, was an over-night expedition using a 33 ft research vessel, the Sheila-B. As the Acrobat tow body was towed along across-isobath transects, it continuously dove and ascended between the surface and within 10 m of the seafloor (down to 35 m depth) (~9 km spatial coverage).

AUV Surveys: The MBARI AUV Dorado is a 12-foot long, 21-inch diameter vehicle with a modular hardware and software design for flexible adaptation of power resources (mission duration) and sensor

payload. The Dorado is equipped to measure: temperature, salinity, oxygen, optical backscattering at two wavelengths (470 and 676 nm), chlorophyll fluorescence, nitrate (NO_3), bioluminescence, and particle size distribution in the range of 0.1 to 250 μm. During LOCO 2005, Dorado surveys focused on mesoscale variability in northern Monterey Bay and its adjacent shelf. During LOCO 2006, Dorado surveys focused on variability entering the primary LOCO array. We deployed drifters that indicated mean surface flow toward the LOCO array from the south, thus the upstream survey domain extended from the array southward to Monterey Canyon. The Dorado's battery power was augmented to enable a 24-hour mission that resolved variability through a tidal cycle via 6 repeat occupations of the transect (~20 km spatial coverage).

RESULTS

Instrument Deployment in the Array Site: All instruments were successfully recovered from the arrays in 2005 and 2006 with no damage to the environment. Data sets from these instruments have been downloaded, backed up in several locations, have been processed and analyzed. Seven manuscripts have resulted directly from this study. Additional data analyses and synthesis are ongoing, we anticipate that several more publications will result from this work.

Small Vessel Surveys: Thus far, the most compelling results from our shipboard work arise from our three 24-h overnight surveys occurring July 12-13, July 18-19 and July 25-26, 2006.

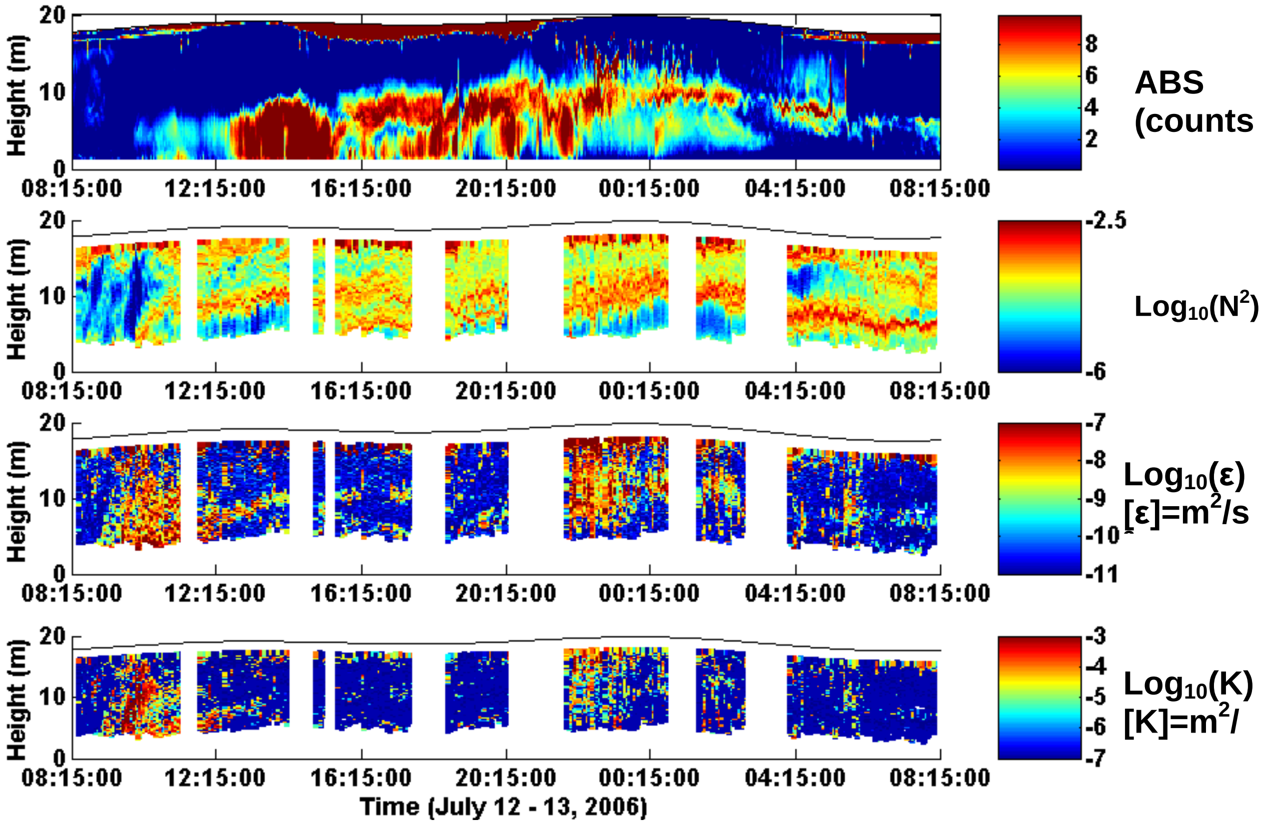

Figure 1: Example of overnight study results, July 12-13, 2006. (a) Acoustic backscatter calculated from co-located ADCP; (b) buoyancy frequency squared from SCAMP measurements; (c) turbulent dissipation rate estimated from Bachelor fit to SCAMP temperature gradient spectra; (d) turbulent diffusion coefficient based on dissipation rate and buoyancy frequency using a flux Richardson number coefficient.

During these overnight studies we anchored in the array (near K1, roughly 18.5 m of water) and profiled continuously with our slow-drop profiler. The ADCP on board also ran continuously during these surveys. The power of these studies lies in the capability of the slow-drop profiler to collect continuous, high-resolution profiles of spectral absorption and attenuation (9 λ) and the vertical structure of the water column during periods of layer formation, maintenance and dissipation. The entire overnight period for July 12-13 is presented in Figure 1. In the top panel, a distinct layer in the acoustic backscatter is evident from about 2300 hours onwards, and is co-located with a strongly stratified layer (2nd panel Figure 1), particularly in the early morning hours. Interestingly, the dissipation of the layer at around 0600 hours is not associated with either a distinct change in the stratification (2nd panel Figure 1) or a pronounced mixing event (3rd and 4th panels Figure 1). As such, it appears that this layer dissipated through a biological process, mostly like migration in response to sunrise (Cheriton et al. 2009, Steinbuck et al. 2009). The layers evident in the backscatter are clearly tied to regions of shear and stratification. As such, our analysis of the data from these surveys is now focusing on the interplay of shear, stratification and turbulent mixing in order to establish how turbulent mixing affects layer evolution. Using a modal decomposition (into barotropic and progressively higher internal modes), it appears that turbulent mixing events are strongly associated with periods in which the internal modes of motion are energized. Energetic internal motions tend to

occur when the barotropic energy is at a minimum, and likely result from the conversion of tidal energy into internal wave motions. Although this analysis is preliminary, it suggests that layer persistence in Monterey Bay may be tied to the tidal cycle due to the disruptive effects of mixing induced by internal tides.

Acrobat Surveys: On a 27-28 July 2006 overnight survey, three coherent chlorophyll patches were observed along two across-shore transects: (1) A broad, sub-surface patch at the offshore end, (2) a near-surface patch at the nearshore end, and (3) a deep patch located between the nearshore and offshore patches. Of the 28 profiles collected along transect 1 and the 25 profiles collected along transect 2, 37 (70%) contained peaks in chlorophyll a fluorescence. Over 35% of these peaks had a thickness < 5 m. Similar to observations by the AUV (presented in the next section), the majority of thin layers we observed in the Acrobat profiles were found inshore of the 25-m isobath. In general, across all transects the thickness and mean depth of peaks at the pycnocline decreased with distance inshore. The results from the Acrobat survey further underscore the heterogeneous horizontal spatial structure of thin layers and also add to the growing evidence suggesting that low-salinity intrusions may be associated with the formation of thin phytoplankton layers over the northern shelf of Monterey Bay (Cheriton et al in press, CSR LOCO special issue).

AUV Surveys: During the 2005 LOCO field program in Monterey Bay, we integrated intensive water column surveys by an autonomous underwater vehicle (AUV) with satellite and mooring data to examine the spatio-temporal scales and processes of phytoplankton thin-layer development. Surveying inner to outer shelf waters repeatedly between August 18 and September 6, the AUV acquired 6,841 profiles. Thin layers were detected in 3,978 (58%) of the profiles. Average layer thickness was 1.4 m, and average intensity was 13.5 $\mu g\ l^{-1}$ above (3.2 x) background. Thin layers were observed at depths between 2.6 and 17.6 m, and their depths showed diurnal vertical migration of the layer phytoplankton populations. Horizontal scales of thin-layer patches ranged from <100 m to >10,000 m. A thin-layer index (TLI), computed from layer frequency, intensity and thinness, was highest in mid-shelf waters, coincident with a frontal zone between bay waters and an intrusion of low-salinity offshore waters (Figure 2).

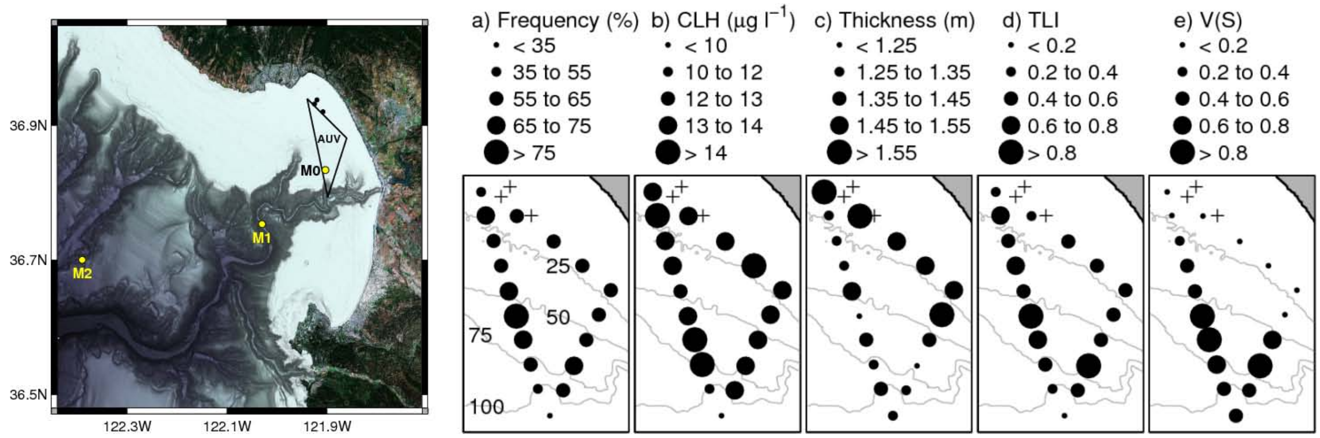

Figure 2. (left) Map of the study region and triangular AUV survey track over the northern shelf in the bay. The 3 black circles in the northeastern bay show the locations of the 2005 LOCO primary mooring sites. (right) Average spatially binned thin-layer attributes, computed from 6,841 AUV profiles, 3,978 of which contained thin-layer structures, from 20 repeated surveys along the track shown (left). Isobaths are shown in gray in all panels; isobath depths (m) are noted in (a). Frequency is the percent of profiles containing phytoplankton thin-layer structures. CLH is chlorophyll line height, a measure of layer intensity above the local background, and TLI is a normalized (0-1 scale) multi-parameter thin-layer index. V(S) is the variance in salinity within the upper 20 m. Data from the M0 (70 m water depth) and M1 (1000 m water depth) moorings provided oceanographic data.

In situ observations indicated that phytoplankton might have been affected by locally enhanced nutrient supply in the convergent upwelling shadow front. Average thin-layer intensity doubled during August 25-29, in parallel with warming at the surface and cooling within and below the thermocline. During this apparent bloom of thin-layer populations, density oscillations in the diurnal frequency band increased by an order of magnitude at the shelf break and in near-bottom waters of the inner shelf, indicating the role of internal tidal pumping from Monterey Canyon onto the shelf. This nutrient transport process was mapped by the AUV. Peak TLI was observed on August 29 during a nighttime survey, when phytoplankton were concentrated in the nutricline. Empirical orthogonal function decomposition of the thin-layer particle size distribution data from this survey showed that throughout the inner to outer shelf survey domain, the layers were dominated by phytoplankton having a cross-section of ~ 50 μm. This is consistent with the size of abundant *Akashiwo sanguinea* cells observed microscopically in water samples (Ryan et al. in press, CSR LOCO special issue)

A Comparison of Offshore AUV and Inner Shelf Acrobat Observations: In 2005, AUV surveys measured offshore, low salinity waters with low chlorophyll a fluorescence. These offshore, low salinity, low chlorophyll a fluorescence waters intruded into inner shelf waters as a subsurface layer, thinning as the layer moved-across shelf. In 2005 and 2006, nighttime profiles and Acrobat surveys detected vertically thin intrusions of low salinity, low chlorophyll a fluorescence water on the inner shelf. Thin layers of fluorescence were detected slightly above these low salinity intrusions on the inner shelf. We hypothesize that in 2005 motile phytoplankton (*Akashiwo sanguinea*) migrated down to the gradient just above these physical intrusions.

Remote Sensing: Remote sensing is critical to understanding the oceanographic variability that influenced the bay environment during the LOCO field programs. Our group has processed MODIS

satellite imagery from both LOCO field programs with custom atmospheric correction using the high-resolution bands of MODIS. This processing produced much higher quality imagery than the standard MODIS processing and revealed major influences of offshore and recently upwelled waters on the bay during the LOCO field programs.

IMPACT/APPLICATIONS

Patterns in biological distribution cannot be interpreted without an understanding of physical oceanographic processes. Through our analysis of simultaneous measurements of physical processes and thin layers, we have found that physical processes from the microscale to the mesoscale each have critical impacts on thin layer dynamics (Dekshenieks et al. 2001, McManus et al. 2003, McManus et al. 2005, Stacey et al. 2007, Cheriton et al. 2007, Ryan et al. 2008, Cheriton et al. 2009, Steinbuck et al. 2009, Cheriton et al. in press, Ryan et al. in press). For this reason, our work provides a critical framework for other ONR LOCO Projects. The ability to make the translation between physical processes over a range of scales, and the mechanisms contributing to thin layer dynamics will ultimately allow us to predict the presence of thin layers in the sea.

RELATED PROJECTS

Related projects: (1) D. Van Holliday & Charles F. Greenlaw (BAE Systems): "Layered Organization in the Coastal Ocean: Acoustical Data, Acquisition, Analyses and Synthesis", (2) Percy L. Donaghay & James M. Sullivan (URI): "Layered Organization in the Coastal Ocean: 4-D Assessment of Thin Layer Structure, Dynamics and Impacts", (3) Timothy J. Cowles (OSU): "Finescale Planktonic Vertical Structure: Horizontal Extent and the Controlling Physical Processes", (4) Jan E.B. Rines (URI): "LOCO: Characterization of Phytoplankton in Thin Optical Layers", (5) David M. Fratantoni & Nelson G. Hogg (WHOI): "The Physical Context for Thin Layers in the Coastal Ocean", (6) Louis Goodman (U Mass Dartmouth): "AUV Turbulence Measurements in the LOCO Field Experiments", and (7) Alfred K. Hanson (URI): "An Investigation of the Role of Nutrient Gradients in the Episodic Formation, Maintenance and Decay of Thin Plankton Layers in Coastal Waters". Additional related projects include (8) Kelly Benoit-Bird (OSU) "Predator effects on dense zooplankton aggregations in the coastal ocean", funded by the ONR Young Investigators Program.

REFERENCES

In the list provided below, the names of graduate students and postdoctoral researchers advised by the PIs on this grant are underlined.

Cheriton OM, MA McManus, DV Holliday, CF Greenlaw, PL Donaghay and T Cowles. 2007. Effects of mesoscale physical processes on thin zooplankton layers at four sites along the West Coast of the U.S. Estuaries and Coasts. 30(4): 1-16. [published]

Cheriton OM, MA McManus, MT Stacey, JV Steinbuck, and JP Ryan. 2009. Physical and biological controls on the maintenance and dissipation of a thin phytoplankton layer. Marine Ecology Progress Series. Vol. 378: 55–69. [published]

Cheriton OM, MA McManus, JV Steinbuck, MT Stacey, JM Sullivan. in press. Towed vehicle observations of across-shelf thin layer structure and a low-salinity intrusion in northern Monterey Bay, CA. Continental Shelf Research. LOCO Special Issue. [in press]

Dekshenieks MM, PL Donaghay, JM Sullivan, JEB Rines, TR Osborn and MS Twardowski. 2001. Temporal and spatial occurrence of thin phytoplankton layers in relation to physical processes. Marine Ecology Progress Series. 223: 61-71. [published]

McManus MA, AL Alldredge, A Barnard, E Boss, J Case, TJ Cowles, PL Donaghay, L Eisner, DJ Gifford, CF Greenlaw, C Herren, DV Holliday, D Johnson, S MacIntyre, D McGehee, TR Osborn, MJ Perry, R Pieper, JEB Rines, DC Smith, JM Sullivan, MK Talbot, MS Twardowski, A Weidemann and JRV Zaneveld. 2003. Changes in characteristics, distribution and persistence of thin layers over a 48-hour period. Marine Ecology Progress Series. 261: 1-19. [published]

McManus MA, OM Cheriton, PT Drake, DV Holliday, CD Storlazzi, PL Donaghay and CE Greenlaw. 2005. The effects of physical processes on the structure and transport of thin zooplankton layers in the coastal ocean. Marine Ecology Progress Series. 301: 199-215. [published]

McManus MA, RM Kudela, MV Silver, GF Steward, JM Sullivan and PL Donaghay. 2008. Cryptic blooms: Are thin layers the missing connection? Estuaries and Coasts. 31: 396-401. [published]

Ryan JP, MA McManus, JD Paduan and FP Chavez. 2008. Phytoplankton thin layers within coastal upwelling system fronts. Marine Ecology Progress Series. 354:21-34. [published]

Ryan JP, MA McManus, JM Sullivan. in press. Interacting physical, chemical and biological forcing of phytoplankton thin-layer variability in Monterey Bay, California. Continental Shelf Research. LOCO Special Issue. [in press]

Stacey MT, MA McManus and J Steinbuck. 2007. Convergences and divergences and thin layer formation and maintenance. Limnology and Oceanography. 52(4): 1523-1532. [published]

Steinbuck JV, MT Stacey, MA McManus, OM Cheriton and JP Ryan. 2009. Observations of turbulent mixing in a phytoplankton thin layer: Implications for formation, maintenance, and breakdown. Limnology and Oceanography. 54(4): 1353–1368. [published]

Sullivan JM, MA McManus, OM Cheriton, KJ Benoit-Bird, L Goodman, Z Wang, JP Ryan, M Stacey, DV Holliday, C Greenlaw, MA Moline, M McFarland. in press. Layered Organization in the Coastal Ocean: An introduction to thin layers and the LOCO project. Continental Shelf Research. LOCO Special Issue. [in press]

PUBLICATIONS

To date, this grant has ***directly*** contributed to seven publications in peer-reviewed journals (2 in press; 2 published in 2009; 2 published in 2008; 1 published in 2007) and one review (1 in press). Additional data analyses and synthesis are ongoing, we anticipate that several more publications will result from this work. In the list provided below, the names of graduate students supported by this grant are underlined.

Cheriton OM, MA McManus, MT Stacey, JV Steinbuck, and JP Ryan. 2009. Physical and biological controls on the maintenance and dissipation of a thin phytoplankton layer. Marine Ecology Progress Series. Vol. 378: 55–69. [published]

Cheriton OM, MA McManus, JV Steinbuck, MT Stacey, JM Sullivan. in press. Towed vehicle observations of across-shelf thin layer structure and a low-salinity intrusion in northern Monterey Bay, CA. Continental Shelf Research. LOCO Special Issue. [in press]

McManus MA, RM Kudela, MV Silver, GF Steward, JM Sullivan and PL Donaghay. 2008. Cryptic blooms: Are thin layers the missing connection? Estuaries and Coasts. 31: 396-401. [published]

Ryan JP, MA McManus, JD Paduan and FP Chavez. 2008. Phytoplankton thin layers within coastal upwelling system fronts. Marine Ecology Progress Series. 354:21-34. [published]

Ryan JP, MA McManus, JM Sullivan. in press. Interacting physical, chemical and biological forcing of phytoplankton thin-layer variability in Monterey Bay, California. Continental Shelf Research. LOCO Special Issue. [in press]

Stacey MT, MA McManus and J Steinbuck. 2007. Convergences and divergences and thin layer formation and maintenance. Limnology and Oceanography. 52(4): 1523-1532. [published]

Steinbuck JV, MT Stacey, MA McManus, OM Cheriton and JP Ryan. 2009. Observations of turbulent mixing in a phytoplankton thin layer: Implications for formation, maintenance, and breakdown. Limnology and Oceanography. 54(4): 1353–1368. [published]

Sullivan JM, MA McManus, OM Cheriton, KJ Benoit-Bird, L Goodman, Z Wang, JP Ryan, M Stacey, DV Holliday, C Greenlaw, MA Moline, M McFarland. in press. Layered Organization in the Coastal Ocean: An introduction to thin layers and the LOCO project. Continental Shelf Research. LOCO Special Issue. [in press]

HONORS/AWARDS/PRIZES

Margaret McManus, University of Hawaii at Manoa

- Aldo Leopold Fellow, 2006
- Promotion to Associate Professor with Tenure, 2007
- Kavli Frontiers Fellow, National Academy of Sciences, 2009

Mark Stacey, University of California, Berkeley

- Promotion to Full Professor, 2009

Olivia Cheriton, University of California Santa Cruz

- Doctorate in Philosophy, 2008

Jonah Steinbuck, Stanford University

- Doctorate in Philosophy, 2009